Three Year Orbital Trim Maneuver Performance of the Cassini Spacecraft Attitude Control Subsystem

Brett A. Smith*

Jet Propulsion Laboratory, California Institute of Technology

Cassini is a sophisticated interplanetary spacecraft providing scientific findings that continue to offer insight into our solar system. After arriving at Saturn on June 30, 2004 it has completed three years of a four year prime mission. To date, Cassini has completed 49 orbits about Saturn and over 40 targeted flybys of Saturn's moons. This has been achieved with a nominal design using three delta-V maneuvers per targeted encounter. Maneuvers are performed using either the bi-propellant main engine (ME) or the mono-propellant reaction control system (RCS). To date, more than 87 Orbital Trim Maneuvers (OTM) have been successfully executed meeting all applicable requirements with margins. This paper summarizes the long-term attitude control performance trends of both types of maneuvers. Operational steps taken by the maneuver team that contributed to the superb performance will also be discussed.

Acronyms

AACS	Attitude and Articulation Control Subsystem
A.U.	Astronomical Unit
c.m.	center-of-mass
DSN	Deep Space Network
EGA	Engine Gimbal Actuator
FSW	Flight Software
HGA	High Gain Antenna
ME	Main Engine
MTA	Mono-propellant Tank Assembly
NAV	Navigation
OTM	Orbit Trim Maneuver
RCS	Reaction Control System
rpm	revolutions per minute
RWA	Reaction Wheel Assembly
S/C	Spacecraft
SOI	Saturn Orbit Insertion
TCM	Trajectory Correction Maneuver
TVC	Thrust Vector Control

Nomenclature

F	Force, N
m	Mass, kg
ΔV	Change in S/C velocity vector (m/s)
S/C	Spacecraft

*Uplink Engineer, Attitude and Articulation Control System, Cassini Spacecraft Operations Office. Mail Stop 230-104, Jet Propulsion Labortory, 4800 Oak Grove Drive, Pasadena, California 91109-8099, USA. Brett.A.Smith@jpl.nasa.gov

I. Introduction

The Cassini spacecraft began its four year prime mission on June 30, 2004, and has been collecting extraordinary images and data from Saturn and its many moons. The AACS subsystem has helped Cassini achieve such great results in part by providing very accurate and consistent Orbital Trim Maneuvers (OTMs). The nominal maneuver strategy is to perform three OTMs per targeted encounter of a moon of Saturn, most often targeting Titan. One maneuver is done near Saturn apoapsis, and one approximately three days before and after the encounter. The reliability and accuracy of these OTMs has helped keep the S/C very close to the designed trajectory to provide the science return.

To date every OTM performed by the Cassini spacecraft has executed as expected, with the desired level of accuracy. The level of performance has given the operations team a high level of confidence in the AACS subsystem during OTMs. While each OTM performed reinforces this confidence, continued analysis of each OTM is done to ensure no negative trends are developing. Performing each OTM with a consistent process helps in trending data from all the OTMs. This paper is written to summarize some of the long term trending analysis for both main engine OTMs and reaction control system maneuvers. This paper will only cover maneuvers since reaching orbit around Saturn, manuvers prior to this time are discussed in (T. Burk, 2005)[1] .

II. Cassini Spacecraft Overview

The Cassini Spacecraft uses two separate propulsion systems to perform OTMs, a bi-propellant main engine and a mono-propellant RCS system. The bi-propellant system produces 445 N of thrust using nitrogen tetroxide and mono-methyl hydrazine. The mono-propellant system is comprised of eight blow-down thrusters using high purity hydrazine. The desired change in S/C velocity (ΔV) determines which system is used, maneuvers less than approximately 300 mm/s are performed as RCS maneuvers while those larger than 300 mm/s are generally performed with the main engine.

As depicted in Figure 1 both the main engine and RCS systems are capable of providing a ΔV to the Cassini spacecraft in the -Z-axis direction. The star-trackers and many of the science instruments' boresights are aligned with the S/C +X direction. While the function of both the ME and RCS systems are used to perform orbit corrections, the two systems are operated in similar but unique methods.

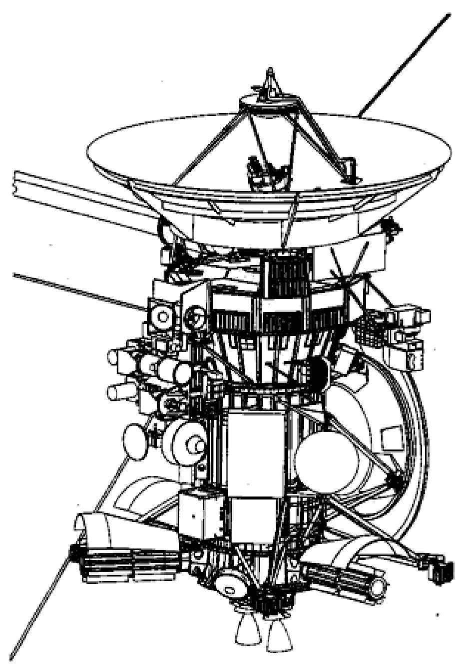

Figure 1. Cassini Spacecraft

All OTMs use a two turn strategy originally designed to meet thermal constraints during the inner solar system cruise mission phase. Designed to keep the Sun off the +X hemisphere of the S/C, this strategy is still used even when thermal constraints are not as severe.[1] (See references for further detail and rational for the two turn design.) ME and RCS OTMs both follow this approach, starting with the HGA pointed at Earth, the spacecraft performs a roll turn about the Z-axis followed by a yaw turn about the Y-axis. Once the thrust axis is aligned with the desired delta-V vector the maneuver is executed. After the thrusting is completed the S/C is unwound reversing each turn returning back to the 'HGA to Earth' attitude. In the following sections ME and RCS maneuvers will be explained in more detail pointing out the differences between the two. More in-depth look at both the RCS and ME subsystems with associated early performance results can be found in (A. Lee, 2005)[2] and (T. Barber, 2002)[3] .

A. Main Engine System

The Cassini Main Engine consists of a bi-propellant 445 N rocket engine. The prime and backup engines are both mounted on the +Z end of the spacecraft and thrust in the -Z direction similar to the RCS thrusters. Two linear actuators gimbal the main engine assembly to provide attitude control about the X and Y axes. The attitude control is achieved with a thrust vector control (TVC) algorithm that commands the gimbal actuators keeping the thrust vector aligned with the actual center-of-mass and reducing the attitude error. Z-axis control is performed by the coupled Y facing RCS thrusters.

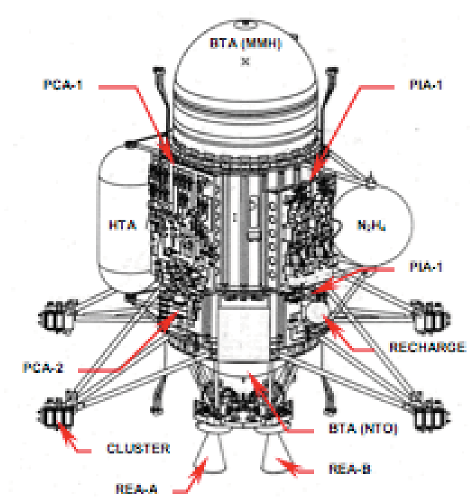

Figure 2. Main Engine System

An accelerometer is aligned with the Z-axis of the spacecraft for providing accurate burn termination to reach the desired ΔV. Prior to a ME OTM the accelerometer is calibrated, producing an estimate of the sensor bias. Both the bias and the angular difference between the accelerometer axis and the ME thrust vector are included in the computation of ΔV imparted on the spacecraft during the OTM. The center of mass is offset from the origin of the spacecraft body frame, therefore an up-dateable pre-aim vector is used to align the thrust vector with the current best estimate of the center of mass. Using the pre-aim helps reduce the initial transient caused by ignition if the thrust vector is not aligned with the center of mass. The ACC bias and pre-aim are all parameters used by the FSW for ME OTMs that are not necessary for RCS base maneuvers.

B. Reaction Control System

The Cassini reaction control system uses eight blow-down hydrazine thrusters for attitude control. A redundant set of eight thrusters also exist but have not been used in flight and will not be discussed. Control about the Z-axis is achieved with coupled Y facing thrusters depicted in Figure 3, imparting very small overall ΔV on the spacecraft. Control about the X-axis and Y-axis is provided by the four Z facing thrusters with two

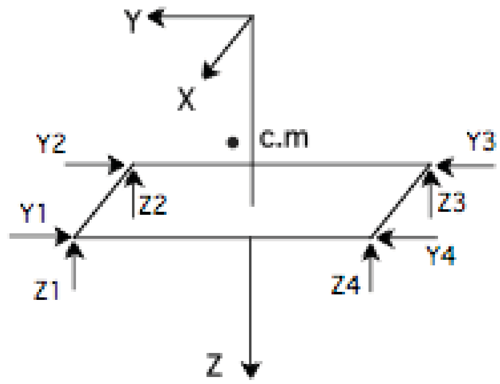

Figure 3. RCS Thruster Geometry

thrusters firing in a pair to rotate the spacecraft about the desired axis (i.e. Z3 and Z4 are fired to provide +X rotation). Not using coupled thrusters when controlling the spacecraft X-axis or Y-axis rotation results in ΔV in the -Z direction. For RCS based OTMs the four prime Z-facing thrusters all fire to provide the desired ΔV. During a RCS OTM the RCS thrusters provide both the thrusting and the attitude control. To control X and Y axis while thrusting, an 'off pulsing' algorithm is used. Maneuvers start with all four thrusters firing, and when the attitude control error about X or Y exceeds a preselected threshold, the appropriate thrusters are pulsed off to allow the spacecraft to rotate back towards the desired attitude. The attitude control error limits, known as 'dead-bands', are set to one-half degree (8.75 mrad) about the X and Y axes. In contrast, thrusters providing the Z axis control are not used to provide ΔV, and therefore are normally off but pulse on when needed to keep the Z-axis rotation within one degree (17.45 mrad) during the OTM.

Unlike the ME OTMs, RCS OTMs do not use an accelerometer and are performed using a timer to specify cutoff. The desired ΔV is commanded to the spacecraft, which is used by the flight computer to compute the thrust duration based on the simple Equation 1.

$$\Delta t = m\,\Delta V/(F) \tag{1}$$

The mass of the spacecraft and the thruster force are tracked on the ground and updated to the AACS flight software prior to an OTM if necessary. Individual thrust values for each thruster are not computed, instead an average thrust level for all thrusters is used.

III. Anatomy of an OTM

Every OTM Cassini performs, either ME or RCS, is based on a ground expanded block sequence for that maneuver type. All OTMs begin and end during a downlink pass with the HGA pointed at Earth. The basic structure is to perform a roll turn keeping the HGA pointed at Earth followed by a yaw turn about the Y-axis to the final burn attitude. After performing the burn, the spacecraft unwinds the yaw turn followed by unwinding the roll turn. This method ensures that no thermal constraints are violated, and the +X axis will always point at least 83 degrees away from the Sun. All OTMs fit into this structure, but RCS and ME OTMs each have some specific aspects.

The main engine block starts by turning on the accelerometer and executing the roll turn. After completing the roll turn using the reaction wheel assemblies (RWA), the RWAs are spun down and turned off. RCS control is used during the yaw turn followed by the accelerometer calibration. During the early cruise a mounting misalignment in the gimbal actuators was discovered using navigation reconstruction. This discovery resulted in the addition of a 0.9 degree fixed offset when aligning the spacecraft with the desired burn vector.[1] The 0.9 degree offset is included after the yaw turn, leaving the S/C at the desired burn attitude. The burn is executed followed by a short settling time to allow the S/C dynamics to damp down before returning to the initial attitude. Each turn is reversed in the same order beginning with the 0.9 degree offset and yaw turn on RCS control. The RWAs are spun up to an intermediate rate so that after the unwind roll turn, the wheel speeds will be at the desired end state.

The reaction control system block is simpler, since all turns are done on RWA control and there is no 0.9 degree offset. After the roll and yaw slews, the S/C is at the burn attitude under RWA control. Just prior to the beginning of the burn the AACS mode is changed to RCS control, however, the RWAs are left spinning at a constant rate. The OTM is performed followed by a settling time before transitioning back to RWA control. Reversing the yaw turn and roll turn under RWA control returns the S/C to the initial attitude. RCS OTM can be as small as 10 mm/s, therefore reducing the thruster firings not aligned with the desired burn direction provides better accuracy for the Navigation team. Performing the yaw turn on RCS control would add ΔV in an undesirable direction that could be larger than the planned burn. Leaving the RWAs spinning during the maneuver also means the end state of the wheel speeds is the same as the initial state. Most of the time, during the same DSN track, a RWA wheel speed bias is performed following the OTM.

IV. Main Engine OTM Performance Trends

Large orbit corrections require the use of the Main Engines to provide a ΔV large enough for the navigation design. The TVC algorithm which keeps the engine thrust vector aligned with the desired ΔV vector and the accelerometer which is used to measure the ΔV produced by the main engine, both contribute directly to the maneuver execution error. The upper plot in Figure 4 shows the ΔV magnitude error as a function of burn duration. Each point represents one OTM ranging from a 1.5 second 238 mm/s maneuver, to a 96.5 second 15.7 m/s maneuver. Magnitude error and pointing error in Figure 4 relate the S/C telemetry value returned with the commanded value of the ΔV vector. The graph shows that the average magnitude error is less than 14.6 mm/s, although the OTM's with a duration less than 5 seconds tend to have larger magnitude error. Presented in a similar way as the magnitude error, the pointing error can be seen in the

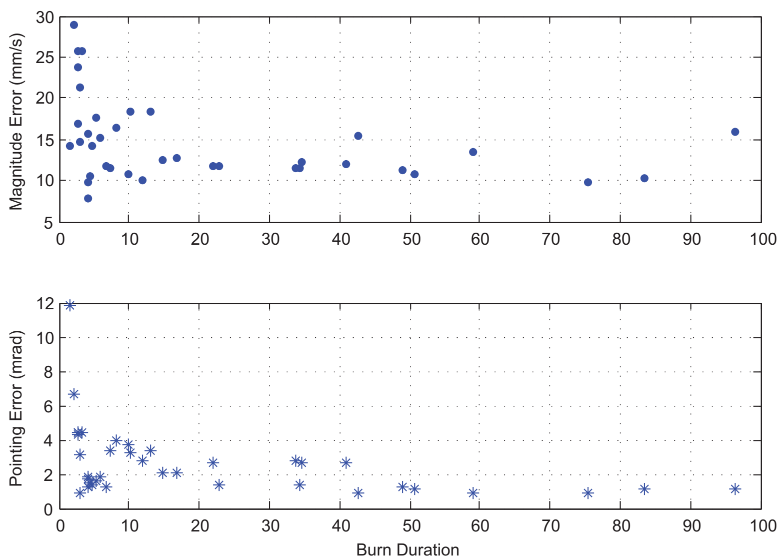

Figure 4. Main Engine OTM Magnitude and Pointing Errors

lower graph of Figure 4. The mean angle error of the executed maneuvers is 2.63 mrad. Larger magnitude and pointing errors seen in the short main engine OTMs are to be expected. As the maneuver duration gets down to below 2 seconds, the errors in knowledge of the tail-off characteristics of the engine, combined with delays in timing of engine cutoff, begin to contribute more to the total error.

In addition to the ΔV trending, the ACC bias calibration performed before every ME OTM is tracked. The accelerometer (ACC) provides the S/C with the ability to provide more accurate ΔV maneuvers. This accuracy is very important to the navigation team so the health of the ACC is monitored closely. The ACC is mounted along the Z-aixs with less than 2 mrad alignment error. The ACC bias calibration is performed prior to each ME OTM by measuring the output while no thrusting is taking place and comparing it with an onboard expected bias value. A drift rate of 2.7 mm/s is the expected value stored within FSW for the ACC bias. If the measured bias during the calibration differs for FSW by more than 2 mm/s the ACC is considered unhealthy and not used for the OTM. In the scenario that the ACC is not used the FSW reverts

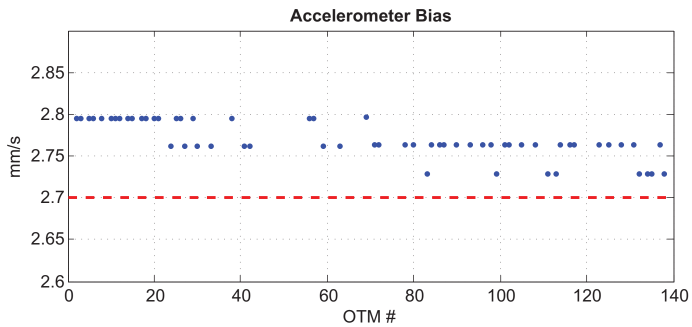

Figure 5. Accelerometer Calibration Bias Values

to a timer, based on the given thrust level and S/C mass, similar to how an RCS OTM is cut-off. To date the ACC has never failed the calibration; however, the bias values are still tracked to ensure no worsening trend developes. Figure 5 shows the bias values from the calibration prior to each ME OTM, with the dashed line representing the FSW expected bias value. It can be seen that with an allowable error of 2 mm/s, the ACC has been very consistent through all ME OTM's with a slight down trend but a total variation of less than 0.1 mm/s.

V. RCS OTM Performance Trends

Cassini RCS OTMs have executed remarkably well to date. The AACS team monitors and trends each of the OTMs as they execute. One of the ways the team trends RCS OTM performance is by tracking the attitude control error and thruster duty cycles seen in each OTM. The major contributor to attitude control error is the offset between the S/C center of mass from the Z-axis. If the RCS system works well it should respond the same to this alignment offset each time. A change in the thrust characteristics of any of the four Z-facing thrusters would change the attitude control error pattern. A second item the AACS team trends is the computed average thruster force seen during each OTM. Accurately predicting the thruster force helps reduce execution error for the navigation team, and also can help indicate any hardware performance issues before a problem occurs.

A. RCS Thruster Force Measurement

RCS OTMs are commanded using parameters of ΔV and thruster force, which are used by the FSW to determine the duration of burn. Without having direct measurement of the thrust it is important to provide the FSW a thrust estimate close to the actual thrust to achieve the desired ΔV. Monitoring the trend in thruster force also provides insight to the propulsion team for the long term performance of the thrusters. Figure 6 shows predicted thruster forces compared to the estimated thruster force for all of the executed RCS OTMs. The square points are the predicted thrust for an OTM, and each diamond represents the calculated thrust value for that OTM. The thruster force is estimated by using the reconstructed ΔV provided from the navigation team, based mainly on doppler shift and the telemetry of the total Z-facing thruster on-time. With the current mass estimate, Equation 1 can be used to solve for the force (N). Figure 6 clearly depicts the slow reduction in thrust as the tank pressure decreases from hydrazine use.

On April 10, 2006 the hydrazine system was re-pressurized (MTA recharge) with helium. The re-pressurization was done to restore the RCS thruster force so it would not fall below a lower threshold before

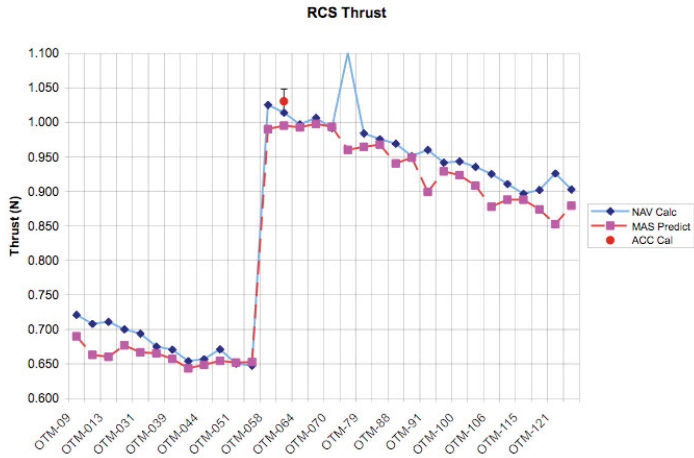

Figure 6. RCS thruster Force Predict and Calculated per RCS OTM

the end of the prime mission. The MTA recharge is evident in the return to 1.0 N thrust at OTM-058. In an effort to have a second independent verification of the MTA recharge success, the accelerometer was used to measure ΔV on OTM-061. Although the RCS thrusters put out just enough thrust for the accelerometer to accurately measure, the calibrated thrust fell within the margin of uncertainty in measurement. The accelerometer based measurement of thrust can be seen in Figure 6 as the round dot with included error bars.

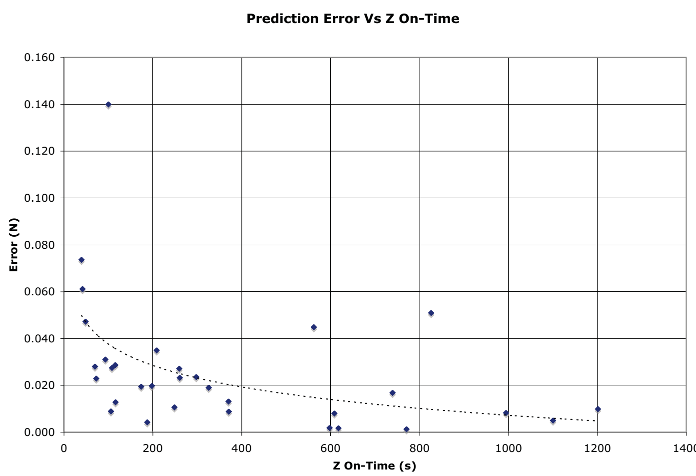

Figure 7. Prediction Error as Function of Thruster On-Time

Figure 7 shows the prediction error of the thruster magnitude with respect to total thruster on-time of all four thrusters. Each point in the graph represents one OTM, with the dashed line indicating a second order fit. During shorter OTMs the transients have a larger effect on the average thrust. As expected the prediction in thrust is better for steady state force than for the force seen while startup transients are present.

B. Duty Cycle and Attitude Control Error

Thruster duty cycle and attitude control error are tied together for RCS OTMs because the off-pulsing algorithm is designed to keep the S/C within the 8.75 mrad deadbands. Since the effective thrust of all four z-facing thrusters does not point through the center of mass, as seen in Figure 3, firing all four thrusters will cause the S/C to rotate about the X and Y axis. Off pulsing provides the ability for the S/C to rotate back towards the desired attitude, while still thrusting. The S/C center of mass changes very slowly due to propellent use and the thruster force is changing at a slow steady rate as well. With the assumption that both the center of mass offset and the thruster force are relatively consistent it is expected to have each RCS OTM perform in a very similar manner. Watching the trends in the attitude control error and duty cycle can give insight to the consistency of performance between OTMs. If the performance of either the duty-cycle or position error were to change dramatically it would give the team an indication to investigate the possible problem, even if the OTM completed within acceptable pointing and ΔV requirements. The change in pressure from the MTA recharge produced a large difference in performance, therefore all performance data and plots are separated into pre-MTA recharge and post-MTA recharge.

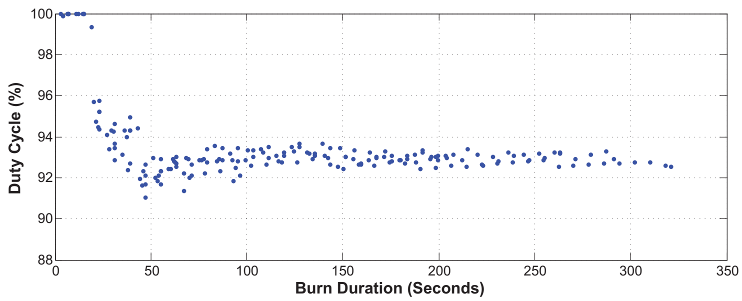

Figure 8. Pre MTA Recharge Duty Cycle Trends

Figure 8 represents the mean thruster duty cycle of all four thrusters as a function of burn duration for all OTMs prior to the MTA recharge. The data in Figure 8 are the cumulative duty cycles computed at each four second telemetry sample and includes 12 OTMs ranging from 65 seconds to over 300 seconds in duration overlaid on the same plot. For these purposes duty cycle is simply the total thruster on time divided by the current burn duration. It can clearly be seen that all thrusters are firing at 100% duty cycle during the first 15 seconds, before the off pulsing begins bringing the duty cycle down to a steady state value of about 93%.

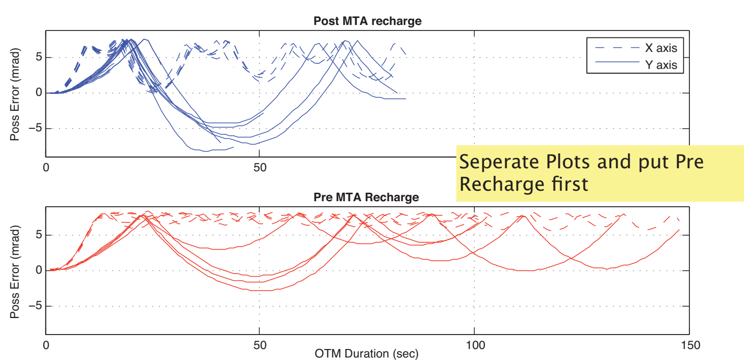

Figure 9. Position Error Trends

During the time prior to MTA recharge the off pulsing algorithm did not generate large off pulses along the X-axis, resulting in the position error staying close to one side of the dead-band, see Figure 9. The frequent but short off pulsing quickly brought the duty cycle to its steady state value of approximately 93%. The position error staying close to the dead-band limits throughout the OTM led to consistent pointing error in the X-axis of close to 8.75 mrad, although the pointing error in these maneuvers was still within the allowable limits. Position error data for the post MTA recharge, seen in Figure 9, shows the difference in the way the off pulsing algorithm is able to keep the S/C attitude off the dead-band. The post MTA recharge position error plot shows the off pulsing algorithm is better suited to the higher thrust by taking larger steps off the dead-band during each maneuver, and allowing the total pointing error for the maneuver to be lower.

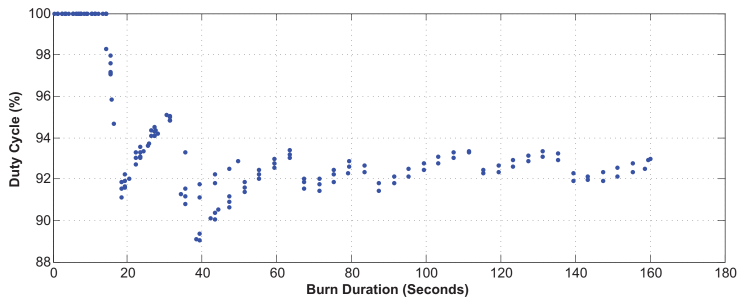

Figure 10. Post MTA Recharge Duty Cycle Trends

The MTA Recharge brought the thruster force back up to approximately 1.0 N which changes the RCS OTM performance. Figure 10 shows the duty cycle as a function of burn duration for all 20 OTMs executed after the recharge. Compared to the pre-recharge data in Figure 8 there are some noticeable differences. At approximately 15 seconds a much longer off pulse brings the duty-cycle down below 92% followed by another long off pulse that can dip down around 90% before the system works back to an average steady state duty-cycle of approximately 93%. The longer duration off pulses that push the X-axis position error away from the dead-band create this shape in the duty cycle plot. Over longer OTMs with either short frequent off pulses or longer less frequent off pulses an average duty cycle of 93% is seen both before and after the MTA recharge. While the large off pulsing provides improved pointing error, the long term average of 93% duty cycle shows that the system continues to operate very consistently, indicating a healthy reaction control system.

VI. Conclusions

The performance of ME and RCS OTMs on the Cassini spacecraft has been very good and quite consistent throughout the Saturnian tour. The RCS thrust magnitude increase from the MTA recharge introduced a change, but the AACS system remains accurate and predictable for all OTMs. This level of repeatability provides confidence that all hardware involved in the system is continuing to work as expected. The high level of accuracy in executing each OTM has provided the navigation team the ability to achieve the targeted Titan flyby altitudes. Through the prime mission this analysis has predominately been looking for early indications of problems in the RCS system performing OTMs. The extended mission brings new opportunities to take advantage of the predictability by improving thrust and duration estimates of each OTM.

VII. Acknowledgments

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